

University of Nebraska - Lincoln

DigitalCommons@University of Nebraska - Lincoln

Kenneth Bloom Publications

Research Papers in Physics and Astronomy

February 2008

Observation and Properties of the Orbitally Excited B^*_{s2} Meson

V. M. Abazov

Joint Institute for Nuclear Research, Dubna, Russia

Gregory R. Snow

University of Nebraska-Lincoln, gsnow1@unl.edu

Kenneth A. Bloom

University of Nebraska-Lincoln, kbloom2@unl.edu

D0 Collaboration

Follow this and additional works at: <https://digitalcommons.unl.edu/physicsbloom>



Part of the [Physics Commons](#)

Abazov, V. M.; Snow, Gregory R.; Bloom, Kenneth A.; and Collaboration, D0, "Observation and Properties of the Orbitally Excited B^*_{s2} Meson" (2008). *Kenneth Bloom Publications*. 232.

<https://digitalcommons.unl.edu/physicsbloom/232>

This Article is brought to you for free and open access by the Research Papers in Physics and Astronomy at DigitalCommons@University of Nebraska - Lincoln. It has been accepted for inclusion in Kenneth Bloom Publications by an authorized administrator of DigitalCommons@University of Nebraska - Lincoln.

Observation and Properties of the Orbitaly Excited B_{s2}^* Meson

V. M. Abazov,³⁶ B. Abbott,⁷⁶ M. Abolins,⁶⁶ B. S. Acharya,²⁹ M. Adams,⁵² T. Adams,⁵⁰ E. Aguilo,⁶ S. H. Ahn,³¹ M. Ahsan,⁶⁰ G. D. Alexeev,³⁶ G. Alkharov,⁴⁰ A. Alton,^{65,*} G. Alverson,⁶⁴ G. A. Alves,² M. Anastasoiaie,³⁵ L. S. Ancu,³⁵ T. Andeen,⁵⁴ S. Anderson,⁴⁶ B. Andrieu,¹⁷ M. S. Anzels,⁵⁴ Y. Arnoud,¹⁴ M. Arov,⁶¹ M. Arthaud,¹⁸ A. Askew,⁵⁰ B. Åsman,⁴¹ A. C. S. Assis Jesus,³ O. Atramentov,⁵⁰ C. Autermann,²¹ C. Avila,⁸ C. Ay,²⁴ F. Badaud,¹³ A. Baden,⁶² L. Bagby,⁵³ B. Baldin,⁵¹ D. V. Bandurin,⁶⁰ S. Banerjee,²⁹ P. Banerjee,²⁹ E. Barberis,⁶⁴ A.-F. Barfuss,¹⁵ P. Bargassa,⁸¹ P. Baringer,⁵⁹ J. Barreto,² J. F. Bartlett,⁵¹ U. Bassler,¹⁸ D. Bauer,⁴⁴ S. Beale,⁶ A. Bean,⁵⁹ M. Begalli,³ M. Begel,⁷² C. Belanger-Champagne,⁴¹ L. Bellantoni,⁵¹ A. Bellavance,⁵¹ J. A. Benitez,⁶⁶ S. B. Beri,²⁷ G. Bernardi,¹⁷ R. Bernhard,²³ I. Bertram,⁴³ M. Besançon,¹⁸ R. Beuselinck,⁴⁴ V. A. Bezzubov,³⁹ P. C. Bhat,⁵¹ V. Bhatnagar,²⁷ C. Biscarat,²⁰ G. Blazey,⁵³ F. Blekman,⁴⁴ S. Blessing,⁵⁰ D. Bloch,¹⁹ K. Bloom,⁶⁸ A. Boehnlein,⁵¹ D. Boline,⁶³ T. A. Bolton,⁶⁰ G. Borissov,⁴³ T. Bose,⁷⁸ A. Brandt,⁷⁹ R. Brock,⁶⁶ G. Brooijmans,⁷¹ A. Bross,⁵¹ D. Brown,⁸² N. J. Buchanan,⁵⁰ D. Buchholz,⁵⁴ M. Buehler,⁸² V. Buescher,²² S. Bunichev,³⁸ S. Burdin,^{43,†} S. Burke,⁴⁶ T. H. Burnett,⁸³ C. P. Buszello,⁴⁴ J. M. Butler,⁶³ P. Calfayan,²⁵ S. Calvet,¹⁶ J. Cammin,⁷² W. Carvalho,³ B. C. K. Casey,⁵¹ N. M. Cason,⁵⁶ H. Castilla-Valdez,³³ S. Chakrabarti,¹⁸ D. Chakraborty,⁵³ K. M. Chan,⁵⁶ K. Chan,⁶ A. Chandra,⁴⁹ F. Charles,^{19,**} E. Cheu,⁴⁶ F. Chevallier,¹⁴ D. K. Cho,⁶³ S. Choi,³² B. Choudhary,²⁸ L. Christofek,⁷⁸ T. Christoudias,⁴⁴ S. Cihangir,⁵¹ D. Claes,⁶⁸ Y. Coadou,⁶ M. Cooke,⁸¹ W. E. Cooper,⁵¹ M. Corcoran,⁸¹ F. Coudere,¹⁸ M.-C. Cousinou,¹⁵ S. Crépe-Renaudin,¹⁴ D. Cutts,⁷⁸ M. Ćwiok,³⁰ H. da Motta,² A. Das,⁴⁶ G. Davies,⁴⁴ K. De,⁷⁹ S. J. de Jong,³⁵ E. De La Cruz-Burelo,⁶⁵ C. De Oliveira Martins,³ J. D. Degenhardt,⁶⁵ F. Déliot,¹⁸ M. Demarteau,⁵¹ R. Demina,⁷² D. Denisov,⁵¹ S. P. Denisov,³⁹ S. Desai,⁵¹ H. T. Diehl,⁵¹ M. Diesburg,⁵¹ A. Dominguez,⁶⁸ H. Dong,⁷³ L. V. Dudko,³⁸ L. Duflot,¹⁶ S. R. Dugad,²⁹ D. Duggan,⁵⁰ A. Duperrin,¹⁵ J. Dyer,⁶⁶ A. Dyshkant,⁵³ M. Eads,⁶⁸ D. Edmunds,⁶⁶ J. Ellison,⁴⁹ V. D. Elvira,⁵¹ Y. Enari,⁷⁸ S. Eno,⁶² P. Ermolov,³⁸ H. Evans,⁵⁵ A. Evdokimov,⁷⁴ V. N. Evdokimov,³⁹ A. V. Ferapontov,⁶⁰ T. Ferbel,⁷² F. Fiedler,²⁴ F. Filthaut,³⁵ W. Fisher,⁵¹ H. E. Fisk,⁵¹ M. Ford,⁴⁵ M. Fortner,⁵³ H. Fox,²³ S. Fu,⁵¹ S. Fuess,⁵¹ T. Gadfort,⁸³ C. F. Galea,³⁵ E. Gallas,⁵¹ E. Galyaev,⁵⁶ C. Garcia,⁷² A. Garcia-Bellido,⁸³ V. Gavrilov,³⁷ P. Gay,¹³ W. Geist,¹⁹ D. Gelé,¹⁹ C. E. Gerber,⁵² Y. Gershtein,⁵⁰ D. Gillberg,⁶ G. Ginter,⁷² N. Gollub,⁴¹ B. Gómez,⁸ A. Goussiou,⁵⁶ P. D. Grannis,⁷³ H. Greenlee,⁵¹ Z. D. Greenwood,⁶¹ E. M. Gregores,⁴ G. Grenier,²⁰ Ph. Gris,¹³ J.-F. Grivaz,¹⁶ A. Grohsjean,²⁵ S. Grünendahl,⁵¹ M. W. Grünewald,³⁰ J. Guo,⁷³ F. Guo,⁷³ P. Gutierrez,⁷⁶ G. Gutierrez,⁵¹ A. Haas,⁷¹ N. J. Hadley,⁶² P. Haefner,²⁵ S. Hagopian,⁵⁰ J. Haley,⁶⁹ I. Hall,⁶⁶ R. E. Hall,⁴⁸ L. Han,⁷ K. Hanagaki,⁵¹ P. Hansson,⁴¹ K. Harder,⁴⁵ A. Harel,⁷² R. Harrington,⁶⁴ J. M. Hauptman,⁵⁸ R. Hauser,⁶⁶ J. Hays,⁴⁴ T. Hebbeker,²¹ D. Hedin,⁵³ J. G. Hegeman,³⁴ J. M. Heinmiller,⁵² A. P. Heinson,⁴⁹ U. Heintz,⁶³ C. Hensel,⁵⁹ K. Herner,⁷³ G. Hesketh,⁶⁴ M. D. Hildreth,⁵⁶ R. Hirosky,⁸² J. D. Hobbs,⁷³ B. Hoeneisen,¹² H. Hoeth,²⁶ M. Hohlfield,²² S. J. Hong,³¹ S. Hossain,⁷⁶ P. Houben,³⁴ Y. Hu,⁷³ Z. Hubacek,¹⁰ V. Hynek,⁹ I. Iashvili,⁷⁰ R. Illingworth,⁵¹ A. S. Ito,⁵¹ S. Jabeen,⁶³ M. Jaffré,¹⁶ S. Jain,⁷⁶ K. Jakobs,²³ C. Jarvis,⁶² R. Jesik,⁴⁴ K. Johns,⁴⁶ C. Johnson,⁷¹ M. Johnson,⁵¹ A. Jonckheere,⁵¹ P. Jonsson,⁴⁴ A. Juste,⁵¹ D. Käfer,²¹ E. Kajfasz,¹⁵ A. M. Kalinin,³⁶ J. R. Kalk,⁶⁶ J. M. Kalk,⁶¹ S. Kappler,²¹ D. Karmanov,³⁸ P. Kasper,⁵¹ I. Katsanos,⁷¹ D. Kau,⁵⁰ R. Kaur,²⁷ V. Kaushik,⁷⁹ R. Kehoe,⁸⁰ S. Kermiche,¹⁵ N. Khalatyan,⁵¹ A. Khanov,⁷⁷ A. Kharchilava,⁷⁰ Y. M. Kharzheev,³⁶ D. Khatidze,⁷¹ H. Kim,³² T. J. Kim,³¹ M. H. Kirby,⁵⁴ M. Kirsch,²¹ B. Klima,⁵¹ J. M. Kohli,²⁷ J.-P. Konrath,²³ M. Kopal,⁷⁶ V. M. Korablev,³⁹ A. V. Kozelov,³⁹ D. Krop,⁵⁵ T. Kuhl,²⁴ A. Kumar,⁷⁰ S. Kunori,⁶² A. Kupco,¹¹ T. Kurča,²⁰ J. Kvita,⁹ F. Lacroix,¹³ D. Lam,⁵⁶ S. Lammers,⁷¹ G. Landsberg,⁷⁸ P. Lebrun,²⁰ W. M. Lee,⁵¹ A. Leflat,³⁸ F. Lehner,⁴² J. Lellouch,¹⁷ J. Leveque,⁴⁶ P. Lewis,⁴⁴ J. Li,⁷⁹ Q. Z. Li,⁵¹ L. Li,⁴⁹ S. M. Lietti,⁵ J. G. R. Lima,⁵³ D. Lincoln,⁵¹ J. Linnemann,⁶⁶ V. V. Lipaev,³⁹ R. Lipton,⁵¹ Y. Liu,⁷ Z. Liu,⁶ L. Lobo,⁴⁴ A. Lobodenko,⁴⁰ M. Lokajicek,¹¹ P. Love,⁴³ H. J. Lubatti,⁸³ A. L. Lyon,⁵¹ A. K. A. Maciel,² D. Mackin,⁸¹ R. J. Madaras,⁴⁷ P. Mättig,²⁶ C. Magass,²¹ A. Magerkurth,⁶⁵ P. K. Mal,⁵⁶ H. B. Malbouisson,³ S. Malik,⁶⁸ V. L. Malyshev,³⁶ H. S. Mao,⁵¹ Y. Maravin,⁶⁰ B. Martin,¹⁴ R. McCarthy,⁷³ A. Melnitchouk,⁶⁷ A. Mendes,¹⁵ L. Mendoza,⁸ P. G. Mercadante,⁵ M. Merkin,³⁸ K. W. Merritt,⁵¹ J. Meyer,^{22,§} A. Meyer,²¹ T. Millet,²⁰ J. Mitrevski,⁷¹ J. Molina,³ R. K. Mommsen,⁴⁵ N. K. Mondal,²⁹ R. W. Moore,⁶ T. Moulik,⁵⁹ G. S. Muanza,²⁰ M. Mulders,⁵¹ M. Mulhearn,⁷¹ O. Mundal,²² L. Mundim,³ E. Nagy,¹⁵ M. Naimuddin,⁵¹ M. Narain,⁷⁸ N. A. Naumann,³⁵ H. A. Neal,⁶⁵ J. P. Negret,⁸ P. Neustroev,⁴⁰ H. Nilsen,²³ H. Nogima,³ A. Nomerotski,⁵¹ S. F. Novaes,⁵ T. Nunnemann,²⁵ V. O'Dell,⁵¹ D. C. O'Neil,⁶ G. Obrant,⁴⁰ C. Ochando,¹⁶ D. Onoprienko,⁶⁰ N. Oshima,⁵¹ J. Osta,⁵⁶ R. Otec,¹⁰ G. J. Otero y Garzón,⁵¹ M. Owen,⁴⁵ P. Padley,⁸¹ M. Pangilinan,⁷⁸ N. Parashar,⁵⁷ S.-J. Park,⁷² S. K. Park,³¹ J. Parsons,⁷¹ R. Partridge,⁷⁸ N. Parua,⁵⁵ A. Patwa,⁷⁴ G. Pawloski,⁸¹ B. Penning,²³ M. Perfilov,³⁸ K. Peters,⁴⁵ Y. Peters,²⁶ P. Pétroff,¹⁶ M. Petteni,⁴⁴ R. Piegaia,¹ J. Piper,⁶⁶ M.-A. Pleier,²² P. L. M. Podesta-Lerma,^{33,‡} V. M. Podstavkov,⁵¹ Y. Pogorelov,⁵⁶

M.-E. Pol,² P. Polozov,³⁷ B. G. Pope,⁶⁶ A. V. Popov,³⁹ C. Potter,⁶ W. L. Prado da Silva,³ H. B. Prosper,⁵⁰ S. Protopopescu,⁷⁴ J. Qian,⁶⁵ A. Quadt,^{22,8} B. Quinn,⁶⁷ A. Rakitine,⁴³ M. S. Rangel,² K. Ranjan,²⁸ P. N. Ratoff,⁴³ P. Renkel,⁸⁰ S. Reucroft,⁶⁴ P. Rich,⁴⁵ M. Rijssenbeek,⁷³ I. Ripp-Baudot,¹⁹ F. Rizatdinova,⁷⁷ S. Robinson,⁴⁴ R. F. Rodrigues,³ M. Rominsky,⁷⁶ C. Royon,¹⁸ P. Rubinov,⁵¹ R. Ruchti,⁵⁶ G. Safronov,³⁷ G. Sajot,¹⁴ A. Sánchez-Hernández,³³ M. P. Sanders,¹⁷ A. Santoro,³ G. Savage,⁵¹ L. Sawyer,⁶¹ T. Scanlon,⁴⁴ D. Schaile,²⁵ R. D. Schamberger,⁷³ Y. Scheglov,⁴⁰ H. Schellman,⁵⁴ P. Schieferdecker,²⁵ T. Schliephake,²⁶ C. Schwanenberger,⁴⁵ A. Schwartzman,⁶⁹ R. Schwienhorst,⁶⁶ J. Sekaric,⁵⁰ H. Severini,⁷⁶ E. Shabalina,⁵² M. Shamim,⁶⁰ V. Shary,¹⁸ A. A. Shchukin,³⁹ R. K. Shivpuri,²⁸ V. Siccaldi,¹⁹ V. Simak,¹⁰ V. Sirotenko,⁵¹ P. Skubic,⁷⁶ P. Slattery,⁷² D. Smirnov,⁵⁶ J. Snow,⁷⁵ G. R. Snow,⁶⁸ S. Snyder,⁷⁴ S. Söldner-Rembold,⁴⁵ L. Sonnenschein,¹⁷ A. Sopczak,⁴³ M. Sosebee,⁷⁹ K. Soustruznik,⁹ M. Souza,² B. Spurlock,⁷⁹ J. Stark,¹⁴ J. Steele,⁶¹ V. Stolin,³⁷ D. A. Stoyanova,³⁹ J. Strandberg,⁶⁵ S. Strandberg,⁴¹ M. A. Strang,⁷⁰ M. Strauss,⁷⁶ E. Strauss,⁷³ R. Ströhmer,²⁵ D. Strom,⁵⁴ L. Stutte,⁵¹ S. Sumowidagdo,⁵⁰ P. Svoisky,⁵⁶ A. Sznajder,³ M. Talby,¹⁵ P. Tamburello,⁴⁶ A. Tanasijczuk,¹ W. Taylor,⁶ J. Temple,⁴⁶ B. Tiller,²⁵ F. Tissandier,¹³ M. Titov,¹⁸ V. V. Tokmenin,³⁶ T. Toole,⁶² I. Torchiani,²³ T. Trefzger,²⁴ D. Tsybychev,⁷³ B. Tuchming,¹⁸ C. Tully,⁶⁹ P. M. Tuts,⁷¹ R. Unalan,⁶⁶ S. Uvarov,⁴⁰ L. Uvarov,⁴⁰ S. Uzunyan,⁵³ B. Vachon,⁶ P. J. van den Berg,³⁴ R. Van Kooten,⁵⁵ W. M. van Leeuwen,³⁴ N. Varelas,⁵² E. W. Varnes,⁴⁶ I. A. Vasilyev,³⁹ M. Vaupel,²⁶ P. Verdier,²⁰ L. S. Vertogradov,³⁶ M. Verzocchi,⁵¹ F. Villeneuve-Seguié,⁴⁴ P. Vint,⁴⁴ P. Vokac,¹⁰ E. Von Toerne,⁶⁰ M. Voutilainen,^{68,||} R. Wagner,⁶⁹ H. D. Wahl,⁵⁰ L. Wang,⁶² M. H. L. S. Wang,⁵¹ J. Warchol,⁵⁶ G. Watts,⁸³ M. Wayne,⁵⁶ M. Weber,⁵¹ G. Weber,²⁴ A. Wenger,^{23,||} N. Wermes,²² M. Wetstein,⁶² A. White,⁷⁹ D. Wicke,²⁶ M. R. J. Williams,⁴³ G. W. Wilson,⁵⁹ S. J. Wimpenny,⁴⁹ M. Wobisch,⁶¹ D. R. Wood,⁶⁴ T. R. Wyatt,⁴⁵ Y. Xie,⁷⁸ S. Yacoub,⁵⁴ R. Yamada,⁵¹ M. Yan,⁶² T. Yasuda,⁵¹ Y. A. Yatsunenko,³⁶ K. Yip,⁷⁴ H. D. Yoo,⁷⁸ S. W. Youn,⁵⁴ J. Yu,⁷⁹ A. Zatserklyaniy,⁵³ C. Zeitnitz,²⁶ T. Zhao,⁸³ B. Zhou,⁶⁵ J. Zhu,⁷³ M. Zielinski,⁷² D. Zieminska,⁵⁵ A. Zieminski,⁵⁵ L. Zivkovic,⁷¹ V. Zutshi,⁵³ and E. G. Zverev³⁸

(D0 Collaboration)

¹Universidad de Buenos Aires, Buenos Aires, Argentina²LAFEX, Centro Brasileiro de Pesquisas Físicas, Rio de Janeiro, Brazil³Universidade do Estado do Rio de Janeiro, Rio de Janeiro, Brazil⁴Universidade Federal do ABC, Santo André, Brazil⁵Instituto de Física Teórica, Universidade Estadual Paulista, São Paulo, Brazil⁶University of Alberta, Edmonton, Alberta, Canada,

Simon Fraser University, Burnaby, British Columbia, Canada,

York University, Toronto, Ontario, Canada,

and McGill University, Montreal, Quebec, Canada

⁷University of Science and Technology of China, Hefei, People's Republic of China⁸Universidad de los Andes, Bogotá, Colombia⁹Center for Particle Physics, Charles University, Prague, Czech Republic¹⁰Czech Technical University, Prague, Czech Republic¹¹Center for Particle Physics, Institute of Physics, Academy of Sciences of the Czech Republic, Prague, Czech Republic¹²Universidad San Francisco de Quito, Quito, Ecuador¹³Laboratoire de Physique Corpusculaire, IN2P3-CNRS, Université Blaise Pascal, Clermont-Ferrand, France¹⁴Laboratoire de Physique Subatomique et de Cosmologie, IN2P3-CNRS, Université de Grenoble 1, Grenoble, France¹⁵CPPM, IN2P3-CNRS, Université de la Méditerranée, Marseille, France¹⁶Laboratoire de l'Accélérateur Linéaire, IN2P3-CNRS et Université Paris-Sud, Orsay, France¹⁷LPNHE, IN2P3-CNRS, Universités Paris VI and VII, Paris, France¹⁸DAPNIA/Service de Physique des Particules, CEA, Saclay, France¹⁹IPHC, Université Louis Pasteur et Université de Haute Alsace, CNRS, IN2P3, Strasbourg, France²⁰IPNL, Université Lyon 1, CNRS/IN2P3, Villeurbanne, France and Université de Lyon, Lyon, France²¹III. Physikalisches Institut A, RWTH Aachen, Aachen, Germany²²Physikalisches Institut, Universität Bonn, Bonn, Germany²³Physikalisches Institut, Universität Freiburg, Freiburg, Germany²⁴Institut für Physik, Universität Mainz, Mainz, Germany²⁵Ludwig-Maximilians-Universität München, München, Germany²⁶Fachbereich Physik, University of Wuppertal, Wuppertal, Germany²⁷Panjab University, Chandigarh, India²⁸Delhi University, Delhi, India²⁹Tata Institute of Fundamental Research, Mumbai, India

- ³⁰University College Dublin, Dublin, Ireland
³¹Korea Detector Laboratory, Korea University, Seoul, Korea
³²SungKyunKwan University, Suwon, Korea
³³CINVESTAV, Mexico City, Mexico
³⁴FOM-Institute NIKHEF and University of Amsterdam/NIKHEF, Amsterdam, The Netherlands
³⁵Radboud University Nijmegen/NIKHEF, Nijmegen, The Netherlands
³⁶Joint Institute for Nuclear Research, Dubna, Russia
³⁷Institute for Theoretical and Experimental Physics, Moscow, Russia
³⁸Moscow State University, Moscow, Russia
³⁹Institute for High Energy Physics, Protvino, Russia
⁴⁰Petersburg Nuclear Physics Institute, St. Petersburg, Russia
⁴¹Lund University, Lund, Sweden, Royal Institute of Technology and Stockholm University, Stockholm, Sweden, and Uppsala University, Uppsala, Sweden
⁴²Physik Institut der Universität Zürich, Zürich, Switzerland
⁴³Lancaster University, Lancaster, United Kingdom
⁴⁴Imperial College, London, United Kingdom
⁴⁵University of Manchester, Manchester, United Kingdom
⁴⁶University of Arizona, Tucson, Arizona 85721, USA
⁴⁷Lawrence Berkeley National Laboratory and University of California, Berkeley, California 94720, USA
⁴⁸California State University, Fresno, California 93740, USA
⁴⁹University of California, Riverside, California 92521, USA
⁵⁰Florida State University, Tallahassee, Florida 32306, USA
⁵¹Fermi National Accelerator Laboratory, Batavia, Illinois 60510, USA
⁵²University of Illinois at Chicago, Chicago, Illinois 60607, USA
⁵³Northern Illinois University, DeKalb, Illinois 60115, USA
⁵⁴Northwestern University, Evanston, Illinois 60208, USA
⁵⁵Indiana University, Bloomington, Indiana 47405, USA
⁵⁶University of Notre Dame, Notre Dame, Indiana 46556, USA
⁵⁷Purdue University Calumet, Hammond, Indiana 46323, USA
⁵⁸Iowa State University, Ames, Iowa 50011, USA
⁵⁹University of Kansas, Lawrence, Kansas 66045, USA
⁶⁰Kansas State University, Manhattan, Kansas 66506, USA
⁶¹Louisiana Tech University, Ruston, Louisiana 71272, USA
⁶²University of Maryland, College Park, Maryland 20742, USA
⁶³Boston University, Boston, Massachusetts 02215, USA
⁶⁴Northeastern University, Boston, Massachusetts 02115, USA
⁶⁵University of Michigan, Ann Arbor, Michigan 48109, USA
⁶⁶Michigan State University, East Lansing, Michigan 48824, USA
⁶⁷University of Mississippi, University, Mississippi 38677, USA
⁶⁸University of Nebraska, Lincoln, Nebraska 68588, USA
⁶⁹Princeton University, Princeton, New Jersey 08544, USA
⁷⁰State University of New York, Buffalo, New York 14260, USA
⁷¹Columbia University, New York, New York 10027, USA
⁷²University of Rochester, Rochester, New York 14627, USA
⁷³State University of New York, Stony Brook, New York 11794, USA
⁷⁴Brookhaven National Laboratory, Upton, New York 11973, USA
⁷⁵Langston University, Langston, Oklahoma 73050, USA
⁷⁶University of Oklahoma, Norman, Oklahoma 73019, USA
⁷⁷Oklahoma State University, Stillwater, Oklahoma 74078, USA
⁷⁸Brown University, Providence, Rhode Island 02912, USA
⁷⁹University of Texas, Arlington, Texas 76019, USA
⁸⁰Southern Methodist University, Dallas, Texas 75275, USA
⁸¹Rice University, Houston, Texas 77005, USA
⁸²University of Virginia, Charlottesville, Virginia 22901, USA
⁸³University of Washington, Seattle, Washington 98195, USA

(Received 2 November 2007; revised manuscript received 22 January 2008; published 28 February 2008)

We report the direct observation of the excited $L = 1$ state B_{s2}^* in fully reconstructed decays to $B^+ K^-$. The mass of the B_{s2}^* meson is measured to be $5839.6 \pm 1.1(\text{stat}) \pm 0.7(\text{syst}) \text{ MeV}/c^2$, and its production rate relative to the B^+ meson is measured to be $[1.15 \pm 0.23(\text{stat}) \pm 0.13(\text{syst})]\%$.

To date, the detailed spectroscopy of mesons containing a b quark has not been fully established. Only the ground $J^P = 0^-$ states B^+ , B^0 , B_s^0 , B_c^+ and the excited 1^- state B^{*} are established according to the PDG [1]. Previous studies of excited ($\bar{b}s$) states have been carried out using inclusive final states, with no mass measurement reported [2]. The properties of ($\bar{b}s$) excited states, and comparisons with ($\bar{b}u$) and ($\bar{b}d$) systems, provide tests of various models of quark bound states and are important for their continuing development.

Quark models predict the existence of four P -wave ($L = 1$) states in the ($\bar{b}s$) system: two broad resonances (B_{s0}^* and B_{s1}') and two narrow resonances (B_{s1} and B_{s2}^*) [3,4]. The broad resonances decay via S -wave processes and therefore are expected to have widths of a few hundred MeV/c^2 . Such states are difficult to distinguish, in effective mass spectra, from the combinatorial background. The narrow resonances decay via D -wave processes ($L = 2$) and should have widths of approximately $1 \text{ MeV}/c^2$ [5], which are strongly dependent on their masses. The B_{s1} width may also be influenced by interference with the wide B_{s1}' state, since they have the same quantum numbers. If the mass of the B_{sJ} ($J = 1, 2$) is large enough, the main decay channel should be $B_{sJ} \rightarrow B^{(*)}K$, since the $B_s\pi$ channel is forbidden by isospin conservation. Recently the CDF collaboration has reported the observation of two narrow resonances consistent with the B_{s1} and B_{s2}^* states [6].

This Letter presents the observation of the process $B_{s2}^* \rightarrow B^+ K^-$ with exclusively reconstructed B^+ mesons, using a data sample corresponding to 1.3 fb^{-1} integrated luminosity collected with the D0 detector [7] at the Fermilab Tevatron collider during 2002–2006. Charge conjugated states are implied throughout this Letter.

The search for narrow B_{sJ} mesons is performed by examining events with $B^{+(*)}K^-$ decays. This sample includes the following decays:

$$B_{s1} \rightarrow B^{*+}K^-, \quad B^{*+} \rightarrow B^+\gamma; \quad (1)$$

$$B_{s2}^* \rightarrow B^{*+}K^-, \quad B^{*+} \rightarrow B^+\gamma; \quad (2)$$

$$B_{s2}^* \rightarrow B^+K^-. \quad (3)$$

The direct decay $B_{s1} \rightarrow B^+K^-$ is forbidden by conservation of parity and angular momentum. In decays (1) and (2), the photons from the B^{*+} decay have energy $E(\gamma) = (45.78 \pm 0.35) \text{ MeV}$ [1]. These photons are not reconstructed in this analysis, so that for such events the invariant mass of the reconstructed decay products is shifted down by $E(\gamma)$.

The data for this analysis were selected without any explicit trigger requirement, although most events satisfy inclusive single-muon triggers. The B^+ mesons are reconstructed in the exclusive decay $B^+ \rightarrow J/\psi K^+$ with J/ψ decaying to $\mu^+\mu^-$. The selection procedure used is ex-

actly as described in Ref. [8]. All B mesons with mass $5.19 < M(B^+) < 5.36 \text{ GeV}/c^2$ are used, which yields a sample of $20915 \pm 293(\text{stat}) \pm 200(\text{syst})$ B^+ candidates.

For each reconstructed B^+ meson, an additional track with transverse momentum (P_T) above $0.6 \text{ GeV}/c$ and charge opposite to that of the B^+ meson is selected. This track is assigned the kaon mass.

For any track i , the significance S_i is defined as $S_i = \sqrt{[\delta_T/\sigma(\delta_T)]^2 + [\delta_L/\sigma(\delta_L)]^2}$, where δ_T (δ_L) is the projection of the track impact parameter on the plane perpendicular to (along) the beam direction, and $\sigma(\delta_T)$ [$\sigma(\delta_L)$] is its uncertainty. Since the B_{sJ} mesons decay at the production point, the additional track is required to originate from the primary vertex by applying the condition on its significance $S_K < \sqrt{6}$. The primary vertex is defined using the method described in Ref. [9].

For each combination satisfying the above criteria, the mass difference $\Delta M = M(B^+K^-) - M(B^+) - M(K^-)$ is computed from the reconstructed meson masses. The resulting distribution of ΔM is shown in Fig. 1.

Of the three decays (1)–(3) through which the B_{sJ} states can reach the ground state B^+ , one or more may be kinematically forbidden if the excited state mass is smaller than the mass of the decay products. From inspection of Fig. 1, there is a single region of excess events above the background at $\Delta M = 67 \text{ MeV}/c^2$; therefore, the fit is based on the hypothesis that only one decay channel is observed. From kinematic considerations it follows that this is the highest energy transition, i.e. $B_{s2}^* \rightarrow B^+K^-$. Alternative hypotheses are discussed later.

Since the decay $B_{s2}^* \rightarrow B^+K^-$ occurs very close to the threshold $\Delta M = 0 \text{ MeV}/c^2$, its width Γ should be around $1 \text{ MeV}/c^2$ [5]. This is much less than the detector resolu-

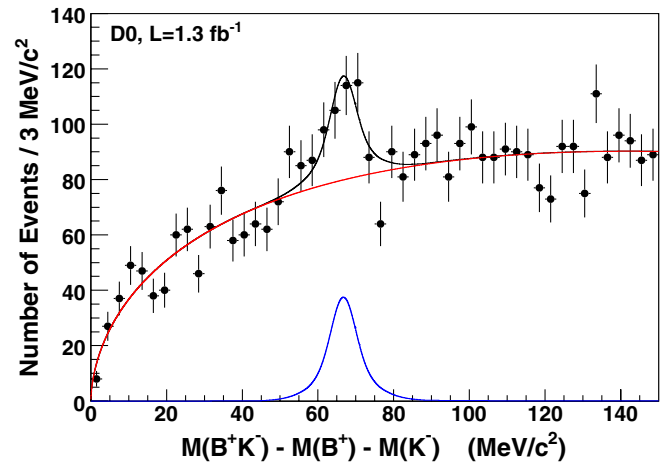


FIG. 1 (color online). Invariant mass difference $\Delta M = M(B^+K^-) - M(B^+) - M(K^-)$ for exclusive B decays. The line shows the fit described in the text, with signal and background contributions also plotted separately.

tion, which is of order $6 \text{ MeV}/c^2$. As a result, the fit is insensitive to values of Γ below $6 \text{ MeV}/c^2$, and Γ is fixed at $1.0 \text{ MeV}/c^2$. This is the width expected for a B_{s2}^* meson with mass as observed in this study. A systematic uncertainty is assigned to this choice of Γ by fitting with a selection of small widths in the range $0\text{--}2 \text{ MeV}/c^2$.

Based on the above, the experimental distribution is fitted to the following function using a binned maximum-likelihood approach:

$$\begin{aligned} F(\Delta M) &= F_{\text{sig}}(\Delta M) + F_{\text{bckg}}(\Delta M), \\ F_{\text{sig}}(\Delta M) &= ND(\Delta M; \Delta_0, \Gamma). \end{aligned} \quad (4)$$

In these equations, Δ_0 is the central position of the resonance, i.e., $M(B_{s2}^*) - M(B^+) - M(K^-)$, Γ is the B_{s2}^* width, and N gives the total number of observed $B_{s2}^* \rightarrow B^+ K^-$ decays. The background is parameterized by a modified power-law function:

$$F_{\text{bckg}}(\Delta M) = c(\Delta M)^k + d\Delta M, \quad (5)$$

where the parameters c , d , and k participate in all fits.

The function $D(\Delta M; \Delta_0, \Gamma)$ in Eq. (4) is the convolution of a relativistic Breit-Wigner function with the experimental Gaussian resolution in ΔM . The width of resonances in the Breit-Wigner function takes into account threshold effects using the Blatt-Weisskopf form factor for $L = 2$ decay [1,10].

The detector resolution function is determined from Monte Carlo simulation. All processes involving B mesons are simulated using the EVTGEN generator [11] interfaced with PYTHIA [12], followed by full modeling of the detector response with GEANT [13] and event reconstruction as in data. The difference between the reconstructed and generated values of ΔM is parameterized by a double-Gaussian function, with the width σ_1 (σ_2) of the narrow (wide) Gaussian set to $2.7 \text{ MeV}/c^2$ ($6.2 \text{ MeV}/c^2$), and the normalization of the narrow Gaussian set to 1.2 times that of the wide Gaussian. Studies of $B^+ \rightarrow J/\psi K^+$ and $D^{*+} \rightarrow D^0 \pi^+$ decays show that simulation underestimates the mass resolution in data by $\approx 10\%$. Therefore, the widths of the Gaussians which parameterise the B_{s2}^* resolution are increased by 10% to match the data, and a 100% systematic uncertainty is assigned to this correction.

Using a fitting range of $0 < \Delta M < 150 \text{ MeV}/c^2$, covering 50 bins, a binned maximum-likelihood fit is performed. The following parameters of B_{s2}^* are obtained:

$$\begin{aligned} \Delta_0 &= M(B_{s2}^*) - M(B^+) - M(K^-) \\ &= 66.7 \pm 1.1(\text{stat}) \text{ MeV}/c^2, \\ N &= 125 \pm 25(\text{stat}) \text{ events}. \end{aligned} \quad (6)$$

Without the B_{s2}^* signal contribution, the log-likelihood of the fit decreases by 13.4, implying that the signal is observed with a statistical significance of more than 4.8σ .

To convert the Δ_0 result into a mass measurement on B_{s2}^* , the PDG values of the B^+ ($5279.1 \pm 0.5 \text{ MeV}/c^2$) and K^- ($493.677 \pm 0.013 \text{ MeV}/c^2$) masses are used as inputs [1]. The uncertainties on these values are included in the systematic uncertainty on the B_{s2}^* mass. In addition, the mass is corrected by an amount ϵ_M to account for the D0 momentum scale uncertainty. This correction is in proportion to the difference between the mass of the B^+ as measured by D0, and as listed by the PDG [1], leading to an upward shift in mass $\epsilon_M = +0.07 \text{ MeV}/c^2$. A 100% systematic uncertainty is assigned to this correction. Taking all factors into account, the mass $M(B_{s2}^*)$ is measured to be

$$M(B_{s2}^*) = 5839.6 \pm 1.1 \pm 0.7 \text{ MeV}/c^2, \quad (7)$$

where the first uncertainty is statistical, the second systematic. Using the detected number of B^+ (20915 ± 293) and B_{s2}^* (125 ± 25) candidates, the production rate of B_{s2}^* relative to that of B^+ is calculated as follows:

$$\begin{aligned} R_J &= \frac{Br(b \rightarrow B_{s2}^* \rightarrow B^+ K^-)}{Br(b \rightarrow B^+)} = \frac{N(B_{s2}^*)}{N(B^+) \epsilon} \\ &= (1.15 \pm 0.23 \pm 0.13)\%. \end{aligned} \quad (8)$$

Here ϵ is the relative detection efficiency of B_{s2}^* events compared to B^+ events; i.e., it is the efficiency to select the additional kaon from the B_{s2}^* decay. The value of this parameter is determined from simulation to be $\epsilon = 0.518 \pm 0.011(\text{stat})$, where the uncertainty results from the finite size of the simulation. Emphasis is placed on agreement between the transverse momentum distributions in data and in simulation, and a systematic uncertainty is assigned to ϵ to account for any difference.

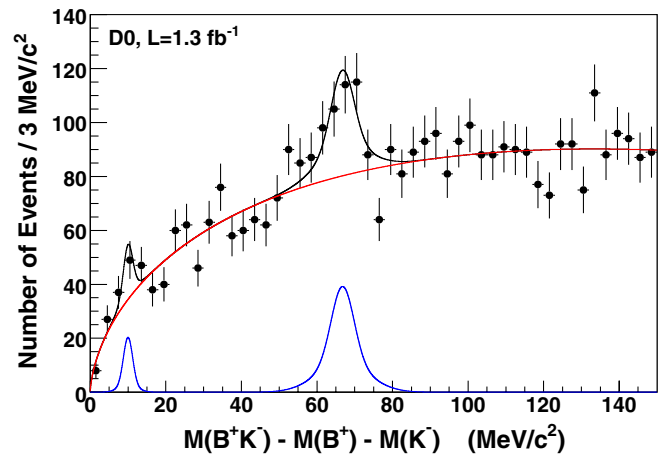


FIG. 2 (color online). Invariant mass difference $\Delta M = M(B^+ K^-) - M(B^+) - M(K^-)$ for exclusive B decays. The line shows the fit with a two-peak hypothesis, as described in the text. Shown separately are contributions from signal and background.

TABLE I. Systematic uncertainties of the B_{s2}^* parameters [described in Eq. (4)] determined from the ΔM fit and from the conversion into the mass $M(B_{s2}^*)$.

Source	$\delta M(B_{s2}^*)$ (MeV/ c^2)	δN
Background parameterization	0.0	3
Bin widths/positions	0.3	7
Value of Γ	0.3	5
PDG mass uncertainties	0.5	0
Momentum scale	0.1	0
Resolution uncertainty	0.1	3
Total	0.7	10

Theoretical models predict that the B_{s2}^* meson, excluding phase-space factors, should decay with equal branching ratios into $B^{*+}K$ and B^+K . Decays into $B^{*+}K$ will be observed as a resonance displaced to lower ΔM by the missing photon energy 45.78 ± 0.35 MeV [1]. An observation of this kind has already been made with the excited states of the $(\bar{b}d)$ quark system [8].

Since the mass difference in the decay $B_{s2}^* \rightarrow B^{*+}K$ is very small, the rate should be strongly suppressed by a factor proportional to $(P^*/P)^5$, where P^* (P) is the momentum in the center-of-mass frame of the kaon in the decay $B_{s2}^* \rightarrow B^{*+}K$ (B^+K) [5]. Using the B_{s2}^* mass as measured here, a suppression factor of 0.074 is calculated; therefore no detectable $B_{s2}^* \rightarrow B^{*+}K$ signal is expected in the ΔM distribution with the current statistics.

To test for the presence of a B_{s1} signal in the data, a two-peak hypothesis is used to fit the ΔM distribution. The B_{s1} peak is assigned a physical width of 0 MeV/ c^2 , and parameterized by a double-Gaussian function representing the experimental detector resolution. The resolution parameters are fixed from a separate simulation of $B_{s1} \rightarrow B^{*+}K^-$ events. In this case, the widths $\sigma_{1,2}(B_{s1})$ of the narrow and wide Gaussians are determined to be 1.1 and 2.2 MeV/ c^2 respectively, and the normalization of the narrow Gaussian is 3.6 times that of the wide Gaussian. Again, the widths of the Gaussians are increased by 10% to correct for underestimation in simulation.

TABLE II. Systematic uncertainties in the B_{s2}^* production rate measurement. The rows show the various sources of systematic uncertainties as described in the text. The columns show the effect of these sources on the three parameters used in the R_J measurement, and on the production rate itself.

Source	$\delta[N(B_{s2}^*)]$	$\delta[N(B^+)]$	$\delta(\epsilon)$	$\delta(R_J)(\%)$
$N(B_{s2}^*)$ uncertainty	10	...	...	0.08
$N(B^+)$ uncertainty	...	200	...	0.01
Reweighting correction	...	...	0.002	0.00
Impact parameter resolution	...	...	0.022	0.05
Track reconstruction efficiency	...	...	0.036	0.08
Statistical effects from simulation	...	...	0.011	0.02
Total	10	200	0.044	0.13

The resulting fit is shown in Fig. 2, giving

$$\Delta M(B_{s1}) = 11.5 \pm 1.4(\text{stat}) \text{ MeV}/c^2, \quad (9)$$

with $25 \pm 10(\text{stat})$ events in the B_{s1} peak. Without the B_{s1} signal contribution, the log-likelihood of the fit decreases by 2.7, implying that this structure is observed with a statistical significance of less than 3σ . Hence with the current data, the existence of a B_{s1} state can be neither confirmed nor excluded. The nominal Q value $\Delta M(B_{s1})$ agrees well with the recent measurement by CDF [6].

The summary of all systematic uncertainties in the B_{s2}^* fit parameters is given in Table I. For the B_{s2}^* mass fit, the influences of different sources of systematic uncertainty are estimated by examining the changes in the fit parameters under a number of variations. A systematic uncertainty is assigned to the background fit by repeating the fit with the parameter k fixed at different values close to its convergence point [see Eq. (5)]. The effect of binning is tested by varying the bin width and position. In addition, the fit is made without the 10% mass resolution correction. To check the effect of fixing the physical width Γ of B_{s2}^* at 1.0 MeV/ c^2 , the fit is repeated with different widths in the range 0–2 MeV/ c^2 . The uncertainty in the absolute momentum scale, which results in a small shift of all measured masses, is assigned a 100% systematic uncertainty. Finally, the uncertainties on the PDG masses of B^+ and K^- [1] are propagated into the systematic uncertainty on the B_{s2}^* mass.

The measurement of the relative production rate R_J uses the kaon detection efficiency predicted in simulation, as well as the numbers of B_{s2}^* and B^+ events. The systematic uncertainty on the number of B^+ events, described in Ref. [8], is ± 200 events. The systematic uncertainty on the number of B_{s2}^* events is ± 10 events.

The uncertainty of the impact parameter resolution in the simulation is estimated to be $\approx 10\%$ [14]. It can influence the measurement of the selection efficiency of the kaon from the B_{s2}^* decay. To test for the effect of such an uncertainty, the efficiency is recalculated with the kaon impact parameter requirement varied by $\pm 10\%$. The resulting variation in efficiency is ± 0.022 .

The track reconstruction efficiency for particles with low transverse momentum is measured in Ref. [15], and good agreement between data and simulation is found. This comparison is valid within the uncertainties of branching fractions of different B semileptonic decays, which is about 7%. This uncertainty translates to an efficiency variation of ± 0.036 . An additional systematic effect, associated with the difference in the momentum distributions of selected particles in data and in simulation, is taken into account. This yields an uncertainty in the efficiency of ± 0.002 .

Combining all these effects in quadrature, the total systematic uncertainty on the efficiency ε is 0.042. Both this and the statistical uncertainty 0.011 on ε must be propagated into the production rate measurement. The effects of contributions from the efficiency, and the number of detected B^+ and B_{s2}^* candidates, are shown in Table II.

In conclusion, the B_{s2}^* state is observed in decays to B^+K^- with a statistical significance of more than 4.8σ . The measured mass is $5839.6 \pm 1.1(\text{stat}) \pm 0.7(\text{syst}) \text{ MeV}/c^2$. This is consistent with results from OPAL [2] and CDF [6]. The B_{s2}^* relative production rate with respect to the B^+ meson is $[1.15 \pm 0.23(\text{stat}) \pm 0.13(\text{syst})]\%$. Searching for a B_{s1} signal gives inconclusive results with the currently available data set.

We thank the staffs at Fermilab and collaborating institutions, and acknowledge support from the DOE and NSF (USA); CEA and No. CNRS/IN2P3 (France); FASI, Rosatom and RFBR (Russia); CAPES, CNPq, FAPERJ, FAPESP and FUNDUNESP (Brazil); DAE and DST (India); Colciencias (Colombia); CONACyT (Mexico); KRF and KOSEF (Korea); CONICET and UBACyT (Argentina); FOM (The Netherlands); Science and Technology Facilities Council (United Kingdom); MSMT and GACR (Czech Republic); CRC Program, CFI, NSERC and WestGrid Project (Canada); BMBF and DFG (Germany); SFI (Ireland); The Swedish Research Council (Sweden); CAS and CNSF (China); Alexander von Humboldt Foundation; and the Marie Curie Program.

*Visitor from Augustana College, Sioux Falls, SD, USA.

[†]Visitor from The University of Liverpool, Liverpool, UK.

[‡]Visitor from ICN-UNAM, Mexico City, Mexico.

[§]Visitor from II. Physikalisches Institut, Georg-August-University Göttingen, Germany.

^{||}Visitor from Helsinki Institute of Physics, Helsinki, Finland.

[¶]Visitor from Universität Zürich, Zürich, Switzerland.

**Deceased.

- [1] W.M. Yao *et al.* (Particle Data Group), J. Phys. G **33**, 1 (2006).
- [2] R. Akers *et al.* (OPAL Collaboration), Z. Phys. C **66**, 19 (1995).
- [3] M. Di Pierro and E. Eichten, Phys. Rev. D **64**, 114004 (2001); E. J. Eichten, C. T. Hill, and C. Quigg, Phys. Rev. Lett. **71**, 4116 (1993).
- [4] D. Ebert, V.O. Galkin, and R.N. Faustov, Phys. Rev. D **57**, 5663 (1998); Phys. Rev. D **59**, 019902(E) (1998).
- [5] A.F. Falk and T. Mehen, Phys. Rev. D **53**, 231 (1996).
- [6] (CDF Collaboration), arXiv:0710.4199v1.
- [7] V.M. Abazov *et al.* (D0 Collaboration), Nucl. Instrum. Methods Phys. Res., Sect. A **565**, 463 (2006).
- [8] V.M. Abazov *et al.* (D0 Collaboration), Phys. Rev. Lett. **99**, 172001 (2007).
- [9] J. Abdallah *et al.* (DELPHI Collaboration), Eur. Phys. J. C **32**, 185 (2004).
- [10] J. Blatt and V. Weisskopf, *Theoretical Nuclear Physics* (John Wiley & Sons, New York, 1952), p. 361.
- [11] D.J. Lange, Nucl. Instrum. Methods Phys. Res., Sect. A **462**, 152 (2001).
- [12] T. Sjöstrand *et al.*, Comput. Phys. Commun. **135**, 238 (2001).
- [13] R. Brun and F. Carminati, CERN Program Library Long Writup W5013 (1993).
- [14] V.M. Abazov *et al.* (D0 Collaboration), Phys. Rev. Lett. **97**, 021802 (2006).
- [15] V.M. Abazov *et al.* (D0 Collaboration), Phys. Rev. Lett. **94**, 182001 (2005).